

PAPER • OPEN ACCESS

## Multi-criteria optimisation of subsonic axial compressor blading

To cite this article: Vitalii Blinov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **643** 012133

View the [article online](#) for updates and enhancements.

### Recent citations

- [Identification of corner separation modelling in axial compressor stage](#)  
Sergey A. Serkov *et al*



The banner features a background image of Earth from space. On the left, there are three circular logos: ECS (Electrochemical Society), The Korean Electrochemical Society, and The Electrochemical Society. The central text reads: "The best technical content in electrochemistry and solid state science and technology!" Below this, a blue bar states: "Available until November 9, 2020." On the right, the PRIME 2020 logo is displayed, with the text "PACIFIC RIM MEETING ON ELECTROCHEMICAL AND SOLID STATE SCIENCE". At the bottom right, a dark blue box contains the text: "REGISTER TO ACCESS CONTENT FOR FREE! ▶"

# Multi-criteria optimisation of subsonic axial compressor blading

Vitalii Blinov<sup>1,\*</sup>, Viacheslav Sedunin<sup>1</sup> and Oleg Komarov<sup>1</sup>

<sup>1</sup> Ural Federal University, Turbines and Engines Department, 620002 Yekaterinburg, Russia

\* E-mail: v.l.blinov@urfu.ru

**Abstract.** The novel approach to parametric topology of the 2D compressor airfoil was tested at multi-criteria optimisation problem for high speed subsonic application. Some results regarding the shape of the blade are presented.

## 1. Introduction

One of the widely spread approaches for the axial compressor blades profiling is using the series of airfoils. For example these are the NACA series, the C-series, and also double-circular-arc and multi-circular-arc airfoils (DCA and MCA) [1]. This approach played a significant role in the compressor development. The main reason here is that all these standard series were extensively studied and tested at wide range of parameters. Starting in the 80's, the prescribed parameters distribution concept was implemented in several designs. Hobbs and Weingold [2] successfully developed a series of Controlled-Diffusion-Airfoils (CDAs) for application in the multistage compressor. Behlke [3] extended the basic CDA philosophy, applied it to the flow region near the end wall and developed new CDAs. Due to the superior aerodynamic performance, CDA aroused considerable research interest around the world [4] and became a part of the design process in leading companies [5, 6].

Nowadays with the use of optimization techniques, the design process of turbomachinery parts can reach higher efficiencies taking into consideration the prescribed limitations [7, 8, 9]. Moreover, the scale of optimization problems today involves part-load conditions [10, 11]. To reduce the computational power needed for airfoil optimisation one has to set up the description of the airfoil itself. So it is essential to represent physical processes involved in the flow, or represent the designer intent to control the flow in a certain way. The novelty of the parameterized topology of the airfoil, presented in this research, is that it is formed from two independent Bezier curves, controlled by these representative parameters. This, first of all, reduces the number of optimisation variables and also allows building up correlations for wide range of operating conditions.

## 2. Geometry description

One of the Bezier curves is the curve of the third order (1) which represents suction side (SS) of the airfoil. Another one is the curve of the fourth order (2) which represents pressure side (PS). More points for the pressure side were given to have additional curvature control next to the leading edge in order to improve operation at negative incidence angles. Leading and trailing edges were made of arcs. General equations for side curves are as follows [12]:

$$P(t) = (1-t)^3 B_0 + 3t(1-t)^2 B_1 + 3t^2(1-t) B_2 + t^3 B_3 \quad (1)$$

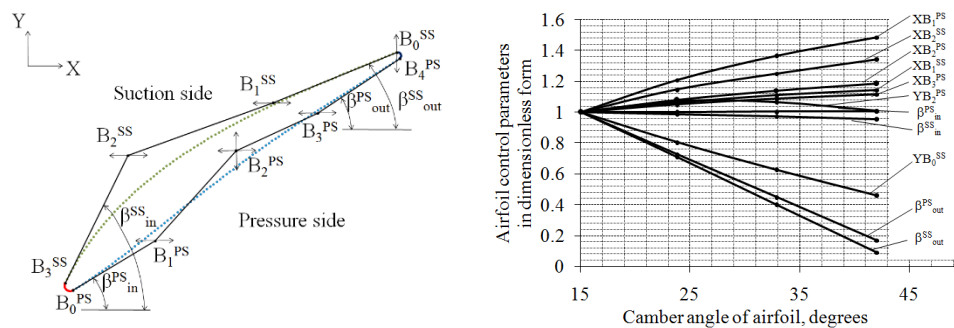


$$P(t) = (1-t)^4 B_0 + 4t(1-t)^3 B_1 + 6t^2(1-t)^2 B_2 + 4t^3(1-t) B_3 + t^4 B_4 \quad (2)$$

Where parameter  $t$  defines position of any point at the curve.

One of the main advantages of this topology is relatively independent parts of both sides, which allows one to obtain specific geometrical features at one side without touching another one (see figure 1 left). Full description of this topology with its physical background could be found in [13, 14, 15]. An in-house code was developed to provide necessary geometrical design in appropriate file format for further automated meshing.

By means of specially designed approximation algorithm, it was possible to get the control parameters for reference airfoils, such as NACA 65, with different turning angles [16]. The obtained values are presented in dimensionless form in figure 1 (right). Continuity of the curves in the figure proves that the approximated airfoil configuration can be used as a starting point in the optimisation procedure. Similar approach, in theory, could be used for wide range of turbo machinery types and applications.



**Figure 1.** 2D airfoil parameters (left) and NACA 65 airfoils configuration described in a way of presented topology (right).

### 3. Optimisation problem set-up

NACA-65 with certain flow turning angle was used as an initial airfoil for optimisation setup. A chain of three major software products were used: IOSO for optimisation processing [17, 18], ANSYS CFX for CFD computations [19] and in-house code for blade profiling [13].

The directions of the geometric parameters change of profiles in the optimisation process are indicated by arrows in Figure 1 (left). The results of the study are a new series of optimal aerodynamic profiles of axial compressor blades in the range of Mach numbers from 0.4 to 0.8.

#### 3.1. Computational model

CFD computations and post-processing were performed in ANSYS CFX. Turbulence model is k-epsilon standard,  $y^+ = 20$ , wall function is scalable. A structured mesh is used for this model. Mesh topology is ATM Optimized. Total mesh size of the domain is 250000 cells. Boundary conditions are the following: hub and shroud surfaces are considered as free slip walls; blade surface is a no slip wall with  $3 \mu\text{m}$  roughness. Total pressure and temperature, velocity vector components at inlet and static pressure at outlet are used. The pressure drop was chosen to achieve the necessary Mach number at the current operating point. The domain has extension of 20% of blade chord at inlet and 100% of chord after the blade. The parameters are computed using mass flow averaged parameters at inlet and outlet sections of the computational domain.

Mesh parameters, boundary conditions and turbulence model were previously tested on compressor airfoil 10A40/15P45 which was widely tested by Bunimovich [20]. Inlet Mach number range is from 0.4 to 0.8, incidence angle is 7.5 to 12 degrees. Also for low Mach number (from 0.1 to 0.3) data from [16] was used which is devoted to NACA series airfoils.

As a result flow turning angle and pressure losses over the whole range were evaluated and compared with experimental data [15, 19].

### 3.2. Optimisation criteria and limitations

Optimisation criteria were maximum flow turning angle and minimum total pressure losses, both are mass flow averaged values at inlet and outlet. For example, the definitions of the flow turning (3) and the total pressure loss coefficient (4) are the following:

$$\Delta\beta = \arctg \frac{w_{out}}{u_{out}} - \beta_{in}, \quad (3)$$

$$\xi = \frac{P_{in}^* - P_{out}^*}{P_{in}^* - P_{in}}, \quad (4)$$

where  $w_{out}$  and  $u_{out}$  are mass flow averaged axial and circumferential velocities;  $\beta_{in}$  is the value of inlet angle taken from inlet boundary conditions;  $P_{in}^*$ ,  $P_{out}^*$  are total pressures, and the remaining is static pressure at the inlet.

The applied limitations could be divided into three groups: geometrical, aerodynamic, and computational.

The geometrical ones are applied due to structural and technological requirements such as minimum blade thickness, required cross-section area, etc. These limitations are controlled at the profiling stage, thus avoiding unnecessary CFD runs. The values of maximum  $C_1$  (5) and minimum  $C_2$  (6) blade thicknesses in percentage of the chord are:

$$C_1 = \left[ \max \left( \sqrt{(x_i^{ss} - x_i^{ps})^2 + (y_i^{ss} - y_i^{ps})^2} \right) \right] \cdot \frac{100\%}{b} \geq 1.5 \cdot D_{in}, \quad (5)$$

$$C_2 = \left[ \min \left( \sqrt{(x_i^{ss} - x_i^{ps})^2 + (y_i^{ss} - y_i^{ps})^2} \right) \right] \cdot \frac{100\%}{b} \geq 1 \cdot D_{out}, \quad (6)$$

where  $x$  and  $y$  are coordinates of tangential points between the airfoil and inner circle at certain chord for pressure side (if ps) and suction side (if ss),  $D_{in}$  and  $D_{out}$  are diameters of leading and trailing edges respectively.

Aerodynamic limitations were applied for flow parameters such as deviation angle and pressure losses. These limitations exclude those solutions, which are most likely being stalled. Computational limitations were used to exclude solutions reached maximum number of iterations without required convergence level of  $10^{-5}$ . Normally, this level could be easily reached for an efficient aerodynamic profile for about 50-150 iterations. So, if the convergence level was not reached within 150 iterations, the solution was considered as unsatisfactory. One of the additional criteria for convergence was the ratio of inlet  $G_1$  to outlet  $G_2$  mass flow:

$$-0.01 \leq \Delta G = \frac{G_1 - G_2}{G_2} \cdot 100\% \leq 0.01, \quad (7)$$

where  $\Delta G$  is mass flow difference in %;  $G_1$  and  $G_2$  are physical values in kg/s.

One of the key airfoil characteristics is the range of stable operation with acceptable level of losses. Therefore, multipoint optimisation must be applied. In current project the applied optimisation was for two points, defining the minimum range (maximum and minimum incidence). It is known that the working range depends on the inlet Mach number and design point flow turning. Total function  $F$  is aimed to be minimized, therefore, could be presented as following:

$$F = \left( \frac{\zeta_i}{\zeta_0} \right)_{\mathbb{N} \geq 1} + \left( \frac{\Delta\beta_0}{\Delta\beta_i} + \frac{\zeta_i}{\zeta_0} \right)_{\mathbb{N} \geq 2}, \quad (8)$$

where 1 and 2 represent the working point;  $\Delta\beta_0$  and  $\Delta\beta_i$  are flow turning angles for initial and i-version of an airfoil respectively;  $\zeta_0$  and  $\zeta_i$  are same for total pressure losses.

#### 4. Results

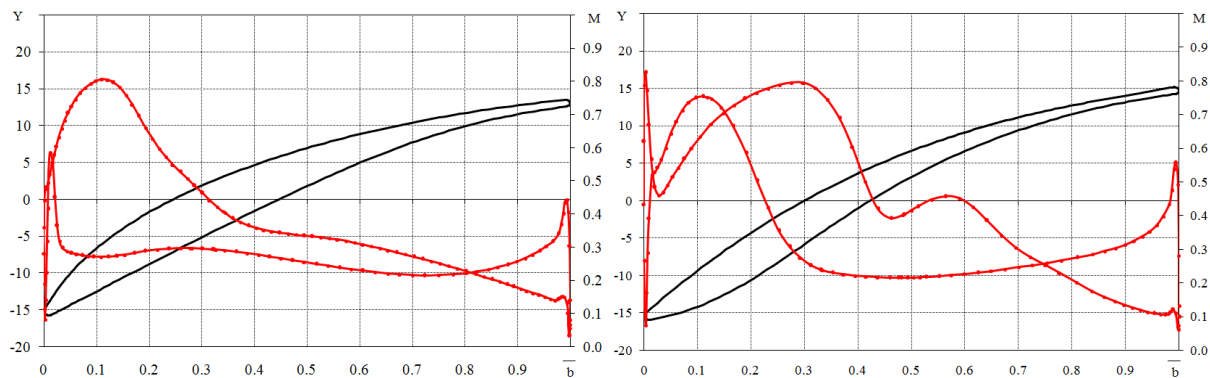
In this section the working range is defined as +3 and -3 incidence angle. In Figure 2 (left) one of the optimal airfoils is shown for inlet Mach number of 0.6, chord to pitch ratio of 1.12, maximum thickness of 10%, inflow angle of  $49^\circ$ , and blade angles difference of  $32^\circ$ . The losses at both operating points are 2.96% and 2.93% with flow turning angle of  $25.63^\circ$  and  $31.45^\circ$  respectively. Velocity profile has a recognizable peak at the first 10% of the suction side. Then there is a constant gradient down to Mach of 0.35 at around 40% of chord and then insufficient slowing down until the trailing edge. At the pressure side the velocity remains almost constant with little shift between Mach of 0.2-0.3. Airfoils with this type of velocity distribution are known as Prescribed Velocity Distribution airfoils (PVD) [1]. The incidence range for this particular airfoil is about  $13^\circ$ .

It is known, that the width of the operating range gets narrower as the inlet Mach number increases [1, 4]. Therefore, special attention was addressed to optimisation at inlet Mach of 0.8, which is referenced as the maximum for purely subsonic flow in the blade channel.

In figure 2 (right) an interesting result of subsequent optimisation is shown. The parameters are as follows: solidity is 1.12, maximum blade thickness is 7% of the chord, blade inlet angle is  $54.8^\circ$ , and camber angle is  $26.6^\circ$  with total pressure losses of 3.0% and 4.4% at +3 and -3 incidence respectively. The range of stable operation is  $10^\circ$ .

The most interesting observation about this airfoil, which could be barely seen at lower Mach numbers, is S-shaped camber line when the inlet part of an airfoil is overturned against the flow direction. This first part of an airfoil lasts for about 30% of chord, and this was the original intention why was the additional control point introduced at the pressure side (see figure 1 left). This shape causes the over speed of the flow on the pressure side (figure 2 right). At the remaining part of the pressure side the velocity is relatively constant with modest increase at the end.

On the suction side the blade inlet angle  $\beta_{in}^{ss}$  is made almost equal to the highest incidence (among applied conditions), which explains low speed at the first part of the profile with further peak at around 0.3-0.45 of the chord, and smaller peak at 0.55 of the chord. This airfoil concept was seen at the entire family of optimised solutions for high Mach number.



**Figure 2.** Mach number distributions along the blade surface at  $M_1 = 0.6$  (left) and  $M_1 = 0.8$  (right).

The key feature of the proposed optimisation approach is that throughout the process the key correlations can be built between desired flow parameters and geometrical ones for different sets of Mach numbers, solidity, blade thickness, etc.

As an example, parameter  $YB0_{ss}$  (see figure 1 left), which prescribes the angle between the blade chord and axial direction, could be approximated for Mach number range of 0.4-0.8 and solidity of 1.3-1.6:

$$Y_{B0_{ss}} = (0.11 \cdot \Delta\beta - 13.17) \cdot M - 0.689 \cdot \Delta\beta + 38.12 \quad (9)$$

Most of the correlations obtained could be described in parabolic form. These correlations can be used for an in-house profiling algorithm in certain range of input variables. It is recommended that the

scope of optimisation setup will cover the entire range of operating conditions of a new compressor design, as extrapolation of such correlations might lead to unclear solutions.

## 5. Conclusions

The airfoil topology was proposed and then used for the optimisation of a set of airfoils, which proved to be efficient both from the computational cost prospective and also as being suitable for further interpolation between optimised solutions. The design approach is based on applying similar topology, then optimising it in an arbitrary range of inlet conditions and blade parameters and then interpolating optimised solutions into particular blade sections.

## Acknowledgments

The work was supported by Act 211 Government of the Russian Federation, contract №02.A03.21.0006.

## References

- [1] Cumpsty N A 1989 Compressor aerodynamics (Longman Scientific & Technical)
- [2] Hobbs D E, Weingold H D 1984 Development of Controlled Diffusion Airfoils for Multistage Compressor Application *Journal of Engineering for Gas Turbines and Power* **106** 271-8
- [3] Behlke R F 1986 The development of a Second Generation of Controlled Diffusion Airfoils for Multistage Compressors *Journal of Turbomachinery* **108** 32-41
- [4] Song B 2003 Experimental and Numerical Investigations of Optimized High-Turning Supercritical Compressor Blades (Doctoral thesis, Virginia Polytechnic Institute and State University, 2003)
- [5] Müller L, Hoeger M, Kožulović D, Stark U 2011 Experimental and numerical evaluation of a high turning transonic compressor stator cascade at flight idle conditions *Proceedings of European Turbomachinery conference* 12
- [6] Smith L H 2002 Axial compressor aerodesign evolution at General Electric, *ASME Journal of Turbomachinery* **124**
- [7] Boiko A V, Govorushenko U N, Erchov S V, Rusanov A V, Severin S D 2002 Aerodynamic calculation and optimal design of the flow part of turbomachines (translation), (NTU "KPI", Kharkov 2002)
- [8] Pini M, Persico G, Dossena V, Robust 2014 adjointbased shape optimization of supersonic turbomachinery cascades, *Proceedings of ASME Turbo Expo*, GT2014-27064
- [9] Shahpar S, Lapworth L, Padram 2003 Parametric design and rapid meshing system for turbomachinery optimisation *Proc of ASME Turbo Expo*, GT2003-38698 (2003)
- [10] Sedunin V A, Komarov O V, Blinov V L, Skorokhodov A V, Procopets A O 2014 The application of modern computational fluid dynamics techniques for increasing the efficiency and stability of an axial compressor in an industrial gas turbine *Energy Production and Management in the 21st Century* **190** 707-19
- [11] Sedunin V A, Brodov Yu M, Komarov O V, Blinov V L, Skorokhodov A V, Serkov S A 2018 Redesign of an axial compressor with mass flow reduction of 30% *Third International Conference on Energy Production and Management in the 21st Century* **222** 93–101
- [12] Rogers D F, Adams J A 1990 Mathematical Elements for Computer Graphics, (second edition, McGraw Hill, NY, 1990)
- [13] Komarov O V, Sedunin V A, Blinov V L 2014 Application of optimisation techniques for new high-turning axial compressor profile topology design, *Proceedings of ASME Turbo Expo*, GT2014-25379
- [14] Blinov V L, Brodov Yu M, Komarov O V, Sedunin V A 2015 Parametric profiling of flat compressor grids for solving multi-objective optimization problems (translation) *Proceedings of higher educational institutions Energy problems* **3-4** 86–95
- [15] Komarov O V, Sedunin V A, Blinov V L, Serkov S A 2016 Optimization approach and some results for 2d compressor airfoil, *International Journal of Gas Turbine Propulsion and Power Systems* **8**(3) 39-46

- [16] Emery J C, Herrig L J, Erwin J R, Felix A R 1958 Systematic two-dimensional cascade test of NACA 65-series compressor blades at low speeds, NACA Report, 1368
- [17] Egorov I N, Kretinin G V, Leshchenko I A, Kuptzov S V 2002 IOSO Optimisation Toolkit - Novel Software to Create Better Design, 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimisation, (Atlanta, Georgia, 2002)
- [18] Dulikravich G S, Dennis B H, Egorov I N, Sobieczky H, Yoshimura S 2003 Parallel Thermo Elasticity Optimization of 3-D Serpentine Cooling Passages in Turbine Blades, Proceedings of ASME Turbo Expo (2003)
- [19] Blinov V L, Brodov Yu M, Komarov O V, Sedunin V A 2015 The choice of parameters of the computational model when solving problems of multi-criteria optimization of flat compressor grids (translation) *Compressors and pneumatics* **1** 36-42
- [20] Bunimovich A I, Svyatogorov A A 1967 Aerodynamic characteristics of flat compressor grids at high subsonic speeds (transl ) *Blade machines and jet apparatus* **2** 5–35